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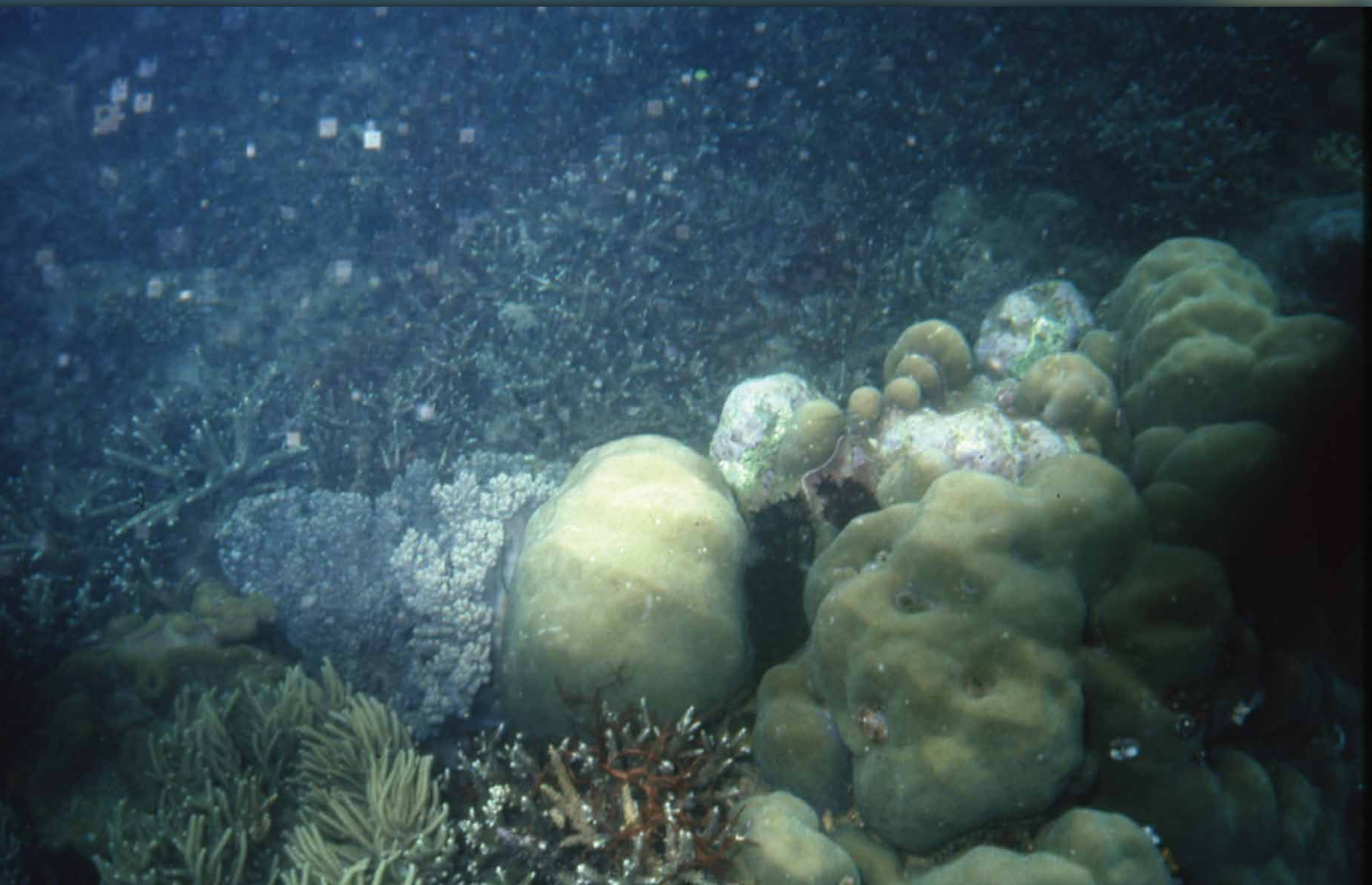
Gold Mining and Submarine Tailings Disposal

Review and Case Study

BY EVAN EDINGER



A fringing coral reef in Buyat Bay, Indonesia, June 2002. This reef at 3 m depth is closest to gold mine tailings outfall. Note high water turbidity, and the mixture of live and dead corals.

ABSTRACT. Environmental impacts associated with submarine tailings disposal (STD) of gold mine wastes vary widely among the relatively few cases studied. The principal contaminants of concern surrounding most gold mines are arsenic, mercury, and cyanide, although antimony, thallium, lead, zinc, and copper may also be important in particular mines. The mineralogy and ore processing techniques associated with different kinds of gold deposits may strongly influence the outcome of STD. Native gold and its associated minerals are generally less toxic than sulfide-mineral gold, in which the gold is incorporated into sulfide minerals in conjunction with other trace elements. Sulfide gold tailings placed in seawater may be particularly dangerous where ore processing includes oxidation by roasting or aggressive chemical leaching, which transforms the sulfide minerals into relatively unstable oxides and oxy-hydroxides.

The case study of the Newmont Minahasa Raya gold mine in Indonesia highlights some of the dangers of gold mine STD. Local villagers observed fish kills shortly after the beginning of STD operations, and they also noted fine red sediment resembling the tailings smothering corals on reefs adjacent to the tailings disposal site. Tailings from this mine dispersed from the intended STD depth of 82 m up to nearby coral reefs, and dispersal extended up to 3.5 km from the end of pipe. Unstable arsenic phases in the tailings accounted for at least 32% of total arsenic in the mine tailings, and less than 10% of total arsenic in fluvially derived marine sediments. Mercury in the submarine tailings was methylated in approximately the same proportions as mercury from artisanal gold mines using mercury amalgamation and in uncontaminated nearshore marine sediments near a watershed with similar bedrock geology. Methyl mercury derived from tailings was incorporated into the local food chain, probably via benthic invertebrates.

INTRODUCTION

Gold has tremendous cultural and economic importance around the world, and gold mining is one of the oldest forms of mining on the planet. Even the Romans noted environmental issues associated with gold mining, particularly from mercury release related to gold ore processing (de Lacerda and Salomons, 1998). The environmental legacy of historical gold mining includes mercury and arsenic contamination of soil, surface water, and groundwater; massive soil erosion; and river degradation associated with placer mining (e.g., Eisler, 2004a). The twentieth-century invention of cyanidation for gold extraction minimized industrial use of mercury for gold extraction, but small-scale gold mining using mercury amalgamation resurged in the 1970s, causing a new wave of mercury contamination resulting from gold mining (de Lacerda and Salomons, 1998).

Submarine tailings disposal (STD), the intentional dumping of mine tailings in the ocean, is a relatively new technique for tailings management, and has rarely been applied to gold mines. A few geologists have advocated subaqueous (in lakes) or submarine tailings disposal as a method to avoid acid mine drainage (AMD) associated with massive sulfide deposits, mostly of base metals such as iron, nickel, copper, and zinc (Pedersen, 2001). AMD results from the oxidation of metal sulfides in mine wastes (or water flow through mine workings) by atmospheric oxygen, releasing sulfuric acid, which then promotes further dissolution of sulfide minerals and toxic metal release, in a positive feedback loop leading to very low pH and very high metal concentrations in solution (Jambor, 2003). Sulfide tailings are stored underwater in tailings ponds to reduce oxygen availability, hence, to avoid AMD. The mining industry often proposes STD as the best solution for tailings management for coastal areas with high seismic activity or rainfall vastly exceeding evaporation, two conditions that potentially threaten the stability of terrestrial tailings pond dams (Ellis et al., 1995). Submarine and subaqueous tailings disposal are both considerably less costly than standard tailings disposal in an artificial structure (Mudd and Boger, in press). An important difference between submarine and subaqueous tailings disposal is that lakes typically have weaker wave and current action than coastal marine settings, and lake sediments experience less bioturbation than marine sediments (Renaut and Gierlowski-Kordesch, 2010).

Where STD has been applied to gold mine tailings (Figure 1), the environmental impacts have been highly variable (Table 1, see case study below, Shimmield et al., 2010, and Rotmann and Thomas, in press). STD has been considered for a number of other gold mines, and pilot studies on tailings toxicity have been carried out, but STD has

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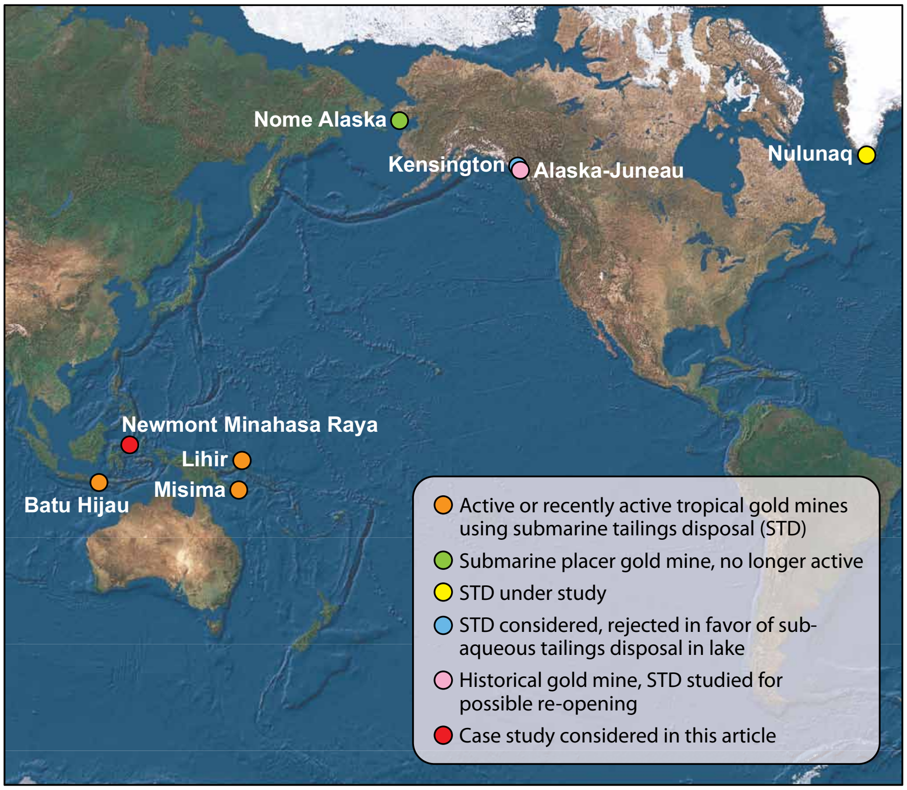

Figure 1. Map showing locations of active, recent past, and proposed gold mines using submarine tailings disposal (STD), and mines that have considered STD, with data published in the scientific literature. See Reichelt-Brushett, in press, for map of additional sites in the coral triangle region.

not (yet) been implemented at these mines (Table 2, Figure 1; see Reichelt-Brushett, in press, for a more extensive list, including sites outside published scientific literature).

GOLD ORE TYPES AND MINERALOGIES, DEPOSIT TYPES, AND PROCESSING TECHNIQUES

Gold commonly occurs naturally as native (metallic) gold. In lode gold deposits, native gold occurs in association with quartz, carbonate minerals, and sulfide minerals hosted in veins or other morphologies, and in igneous or metamorphic rocks. Native gold is also concentrated in placer deposits resulting from surficial erosion and hydraulic concentration of the primary lode gold deposits. Historically, the largest volume of gold has been extracted from primary native gold deposits. The sulfide (and sometimes selenide and/or telluride) minerals associated with native gold often contain significant amounts of arsenic and mercury. These minerals are released to the environment in tailings during initial milling and separation of the gold ores. For example, arsenic and mercury associated with historical lode gold mining in the Meguma terrane of eastern mainland Nova Scotia, Canada, have led to significant arsenic and mercury contamination of watersheds (e.g., Walker et al., 2009). Groundwater in such areas is often significantly contaminated with arsenic, for example, in Nova Scotia, Canada (Jamieson, 2011), and there are many European examples (reviewed in Magalhães, 2002).

Not all native gold deposits are rich in arsenic and mercury. Porphyry copper-gold deposits, such as the Batu Hijau deposit in Sumbawa, Indonesia (Gwyther et al., 2009), or Bougainville, Papua New Guinea, contain almost no arsenic. In these cases, copper is often the main source of toxicity, particularly to molluscs, and the sedimentation is the principal threat to epifauna (Jeffery, 1988).

Because native gold is not chemically bound as a solid solution in associated sulfide minerals, larger particles of native gold can be extracted by mechanical means, such as crushing and milling of lode deposits or hydraulic sorting of placer deposits (gold pans, sluice boxes, and other traditional mining techniques). Smaller particles of native gold are extracted by mercury amalgamation, a very old technique, used extensively by the Romans and in medieval Spain (de Lacerda, 2003).

Because mercury and gold have a natural affinity for each other, applying liquid mercury to crushed ore extracts gold from those materials as a mercury-dominant alloy (amalgam). Heating then volatilizes the mercury, which is sometimes captured for re-use in retorts or reflux systems. Mercury release from gold mining by mercury amalgamation is a major source of mercury release to the environment, particularly in developing world locations not affected by other industrial sources of mercury such as extensive coal combustion or the chlor-alkali industry (de Lacerda, 2003). Tailings from native gold deposits treated with mercury amalgamation leave considerable mercury residues. Mercury contamination from historical mining activities has caused high levels of soil mercury contamination in Australia, California, and elsewhere (de Lacerda and Salomons, 1998; Churchill et al., 2004; Alpers et al., 2005).

In some gold deposits, gold occurs wholly or partially as a chemically bound solid solution constituent of pyrite (FeS_2), arsenian pyrite, or arsenopyrite ($FeAsS$). In some sediment-hosted disseminated gold deposits, pyrite or arsenopyrite (and sometimes additional sulfide minerals, including orpiment [As_2S_3], realgar [As_4S_4], stibnite [Sb_2S_3], and cinnabar [HgS]) precipitated in sedimentary rocks as a result of hydrothermal fluid migration. They are broadly termed Carlin-type deposits, after the Carlin Trend of northern Nevada, USA. Carlin-type deposits typically have anomalously high occurrences of four toxic elements: arsenic (As), antimony (Sb), thallium (Tl), and mercury (Hg). Most known Carlin-type deposits are mined in continental settings far from the ocean. However, some are exploited in coastal environments—and one mine exploiting a Carlin-like deposit has used STD (Newmont Minahasa Raya mine; Turner et al., 1994; see case study below).

Because arsenic is a metalloid, having properties that are in between those of metals and nonmetals, it reacts differently from other toxic heavy metals during ore processing (Magalhães, 2002). The processing techniques for sulfide ores, which involve oxidation of the ore by roasting or chemical leaching, convert gold-bearing pyrite and arsenopyrite into less environmentally stable minerals, often iron oxides and oxy-hydroxides (e.g., Burns and Burns, 1979; Weeks and Wan, 2000). Although sulfide base metal

Table 1: Gold mines using submarine tailings disposal (STD).

Mine Name	Country	Deposit Type	Major Contaminants of Concern	Sample References in Primary Scientific Literature
Nome Offshore Placer Project	Alaska, USA	Submarine placer	Sediment	Jewett et al. (1999)
Misima	Papua New Guinea	Epithermal Carbonate base-metal Au-Ag	Pb, Zn	Fallon et al. (2002); Shimmield et al. (2010)
Lihir	Papua New Guinea	Proximal quartz-sulfide-gold	Cu, As, Cd, Hg, Pb	Brewer et al. (2007); Shimmield et al. (2010) Rotmann and Thomas, (in press)
Batu Hijau	Indonesia	Porphyry copper with gold	Cu	Gwyther et al. (2009); Sahami et al. (2011)
Newmont Minahasa Raya	Indonesia	Sediment-hosted hypothermal (Carlin-type)	As, Sb, Hg, Tl	Edinger et al. (2007, 2008); Blackwood and Edinger (2007); Lasut et al. (2010)

Table 2. Gold mines where submarine tailings disposal (STD) was considered and experimental treatments were published in scientific literature. This list focuses on high-latitude sites (see Reichelt-Brushett, in press, for a list of gold mines proposing STD within the coral triangle region).

Mine Name	Country	Deposit Type	Major Contaminants of Concern	Sample References in Primary Scientific Literature
Kensington	Alaska, USA	Carbonate-hosted gold vein	Pb, Zn	Kline and Stekoll (2001)
Alaska-Juneau	Alaska, USA	Carbonate-hosted gold vein	Pb, Zn	Johnson et al. (1998a,b)
Nalunaq	Greenland	Mesothermal gold vein	As, Cu, Cd, Cr	Matthies et al. (2011)

ores are relatively unreactive in water, due to the dearth of oxygen, arsenic incorporated into metastable iron oxides and oxy-hydroxides, or other metastable minerals, becomes more soluble under reducing conditions. Thus, arsenic incorporated into metastable phases such as Fe-oxy-hydroxides can dissolve into sediment pore water and migrate vertically, returning to the sediment-water interface, where it again precipitates (Martin and Pedersen, 2002). The dissolution and re-precipitation of arsenic in these metastable phases also permits transformations of arsenic between its less-toxic As-V and more toxic As-III chemical forms (e.g., Walker et al., 2009). Inorganic arsenic readily bioaccumulates, but does not generally biomagnify up the marine food chain (Magalhães, 2002). When arsenic is methylated, or otherwise complexed into organoarsenic compounds, it becomes more biologically available and more toxic than its inorganic forms (e.g., Andreae and Klumpp, 1979; Eisler, 2004b).

In theory, STD relies on natural sedimentation to bury mine tailings beneath uncontaminated sediments, thus isolating the tailings from biological activity (Ellis, 2008). This conceptual model of STD depends on rapid sedimentation rates, and it fails to account for sediment failures and slumping (e.g., Burd et al., 2000) or for bioturbation, the ability of deposit-feeding benthic biota to vertically mix sediment. When partially buried tailings on sloping bottoms slump, they may become exposed at the surface again, increasing the potential for their contact with benthic fauna (Burd et al., 2000). Mine tailings are typically low in organic matter and high in toxic metals and metalloids, and should be unattractive to deposit-feeding biota. Bioturbating fauna can mix shelf-depth sediments down to 1 m depth, and continental slope sediments to a shallower depth. Because of the natural tendency of arsenic to dissolve under reducing conditions below the sediment-water interface, percolate upward, and reprecipitate under more oxidizing conditions, deposit-feeding fauna may be exposed to arsenic-laden sediment pore water, providing a potential pathway for contamination into the food chain (Blackwood and Edinger, 2007). The reducing, acidic gut tracts of many deposit-feeding invertebrates (Ahrens and Lopez, 2001) can transform the mineralogy of clay particles (Needham et al., 2004), supporting the notion that deposit-feeding invertebrates can accelerate the diagenesis of arsenic in submarine mine wastes from more stable to less-stable forms, and transfer arsenic into the food chain. When different fish species living near submarine gold mine tailings in Indonesia were tested, the demersal fish feeding on benthic invertebrates on flat sandy or muddy bottoms typically exhibited the highest arsenic burdens (Shepherd-Miller Inc., 2001).

MERCURY RELEASE

Although most mercury contamination associated with gold mining comes from past or present mercury amalgamation (e.g., de Lacerda and Salomons, 1998), mercury is present in many gold deposits as an associated trace element. Mercury present as cinnabar (mercuric sulfide, HgS) is relatively refractory, like pyrite, but ore processing techniques may transform mercury to more labile forms (Eisler, 2004c). Cyanidation may facilitate Hg release where residual cyanide remains in tailings (e.g., Shaw et al., 2006). Once mercury is available at the sediment-water interface as metallic mercury or in metastable phases, it can be methylated by bacterially mediated processes (de Lacerda and Salomons, 1998). Methyl mercury is acutely toxic and readily biomagnifies up marine food webs.

CYANIDE

Cyanidation has been used since the 1930s to extract gold from ore in a variety of processes, including heap-leach of crushed ore, or contained cyanide leach of processed ore (Eisler, 2004a). Although cyanide does not generally persist in the environment as do heavy metals and metalloids, it is acutely toxic. Cyanide's toxicity has been an obvious impediment to attempts to provide alternatives to mercury amalgamation in small-scale gold mining. Although cyanide used in treating gold ores is meant to be detoxified by oxidation to cyanate before tailings are discharged, low concentrations of cyanide often persist in gold mine tailings, and may be gradually released to the environment over protracted periods (Shaw et al., 2006). While gold-mining-related cyanide impacts on wildlife in terrestrial settings have been extensively studied (e.g., Eisler 2004a; Donato et al., 2007), the impacts of cyanide residues in submarine tailings are relatively unknown. Residual cyanide toxicity may limit colonization of freshly deposited gold mine tailings on the seabed, but the duration and severity of this impact are unknown.

SEDIMENT QUALITY GUIDELINES

Sediment quality guidelines have been proposed as effective approaches to preventing chemical and biological impacts on marine biological communities (CCME, 2002; Bjørgesæter and Gray, 2008). Canadian Council of Ministers of Environment (CCME) sediment quality guidelines include two concentrations for many contaminants: a recommended sediment quality guideline (SQG), and a probable effects level (PEL). For example, the CCME interim marine sediment quality guideline (IMSQG) for arsenic is 7.5 ppm, while the PEL for arsenic in marine sediments is 41 ppm. Background arsenic concentrations in uncontaminated marine sediments from gold districts may easily exceed the IMSQG for arsenic. By contrast, the PEL is toxicologically based and indicates a contaminant level at which biological impacts on organisms can be expected, and below which impacts are not predicted. Because the concentration at which a given contaminant has toxicological effects varies among organisms and environments, other authors have suggested that a suitable rule of thumb for sediment quality is for contaminant concentrations not to exceed four times background levels (Bjørgesæter and Gray, 2008). CCME guidelines are based on whole sediment concentrations, but most studies use the silt and clay fraction (< 63 μm) only, as this standardization avoids most grain-size biases. Grain-size biases are particularly important in mixed carbonate-siliciclastic sediments, in which the coarser biogenic carbonate fraction of the sediment contains far lower trace element concentrations than the finer siliciclastic fraction (David, 2002). Although sediment quality guidelines are used as reference values, they have no legal or regulatory status.

> “VERY FEW ENVIRONMENTAL STUDIES OF INTENTIONAL PLACEMENTS OF GOLD MINE TAILINGS IN THE OCEAN HAVE BEEN PUBLISHED IN THE SCIENTIFIC LITERATURE.”

SEDIMENTATION AND TAILINGS DISPERSAL

Apart from the toxins contained in gold mine tailings, the increased sedimentation rates associated with submarine tailings disposal may have a biological impact on surrounding benthic marine communities. These impacts do not differ in nature from sedimentation associated with STD of other types of mine tailings, which have been extensively reviewed elsewhere (e.g., Ellis et al., 1995; Burd et al., 2000; Blanchette et al., 2001; Ellis, 2008).

One of the greatest concerns with STD is dispersal of mine tailings away from their intended disposal site by waves, currents, or sediment mass transport (Burd et al., 2000; Ellis, 2008). Although STD avoids the risks of tailings dam failure, it gives up the ability to control what happens to the tailings after they are released to the ocean. Coastal ocean waters are far more dynamic depositional environments than lakes (Renaut and Gerlowski-Kordesch, 2010), with the potential action of surface waves, internal waves, tidal currents, contour currents, storm-induced scour and currents, and tsunamis. Therefore, submarine tailings disposal in the ocean involves far greater risks of tailings mobility than subaqueous tailings disposal in lakes or artificial tailings ponds (Pedersen, 2001). Proponents of STD have argued that tailings disposal into deep water (> 150 m) minimizes risks because most human exploitation of marine species is from shallow-water environments such as coral reefs (e.g., Ellis et al., 1995; Ellis, 2008). This assumption fails to recognize the diversity of deepwater fauna such as corals and fishes, particularly around submarine canyons (e.g., Sink et al., 2006; De Leo et al., 2010), where STD outfalls are frequently placed (e.g., Shimmield et al., 2010). Furthermore, human exploitation of the sea has expanded into deeper waters in many parts of the world, as shallow-water fish stocks become depleted (Pauly et al., 2005).

CASE STUDY | STD at the Newmont Minahasa Raya Gold Mine, Indonesia

Very few environmental studies of intentional placements of gold mine tailings in the ocean have been published in the scientific literature. Published examples include discussions of the Newmont Minahasa Raya (NMR) gold mine in North Sulawesi, Indonesia, along with the Lihir and Misima gold mines in Papua New Guinea (Fallon et al., 2002; Brewer et al., 2007; Rotmann and Thomas, in press). Ironically, the NMR mine was intensively studied because of difficulties with the STD system, and because of complaints by the local population, which were acted upon by the Indonesian government and by Indonesian and foreign nongovernmental environmental organizations. The mine used a relatively shallow STD system, with the pipe ending at 82 m water depth, and it was an unusual deposit type for tropical island settings where STD is often advocated.

The NMR gold mine was a relatively small deposit that was mined from 1996 to 2004 to exploit a sediment-hosted Carlin-like deposit with As-Sb-Hg-Tl anomalies (Turner et al., 1994). Volcanic rocks in the watersheds surrounding the mine hosted native gold deposits that were exploited by small-scale miners using mercury amalgamation. The confusion induced by multiple sources of mercury contamination contributed to the virulence of the controversy surrounding STD at the NMR mine. The STD system for this small mine deposited only 2,000 tonnes per day of tailings, mixed 7:1 with seawater, into waters 82 m deep, approximately 900 m from shore. Although this tailings outfall depth was shallower than that of most modern STD operations, which usually have tailings outfalls deeper than 100 m (Ellis, 2008), and it was on a gentler slope than usually recommended, the STD system for this mine was operated according to its permits from the Indonesian government. The average concentrations of arsenic, antimony, and mercury in the tailings sampled in 2002 and 2004 were 590–690 ppm As, 490–580 ppm Sb, and 0.8–5.8 ppm Hg, about 20–30 times higher than the pre-mining average arsenic concentration in local seafloor sediments (Edinger et al., 2007). These concentrations are consistent with those predicted in the environmental impact assessment (PTNMR, 1994) for the mine and in ore-processing testing procedures (Weeks and Wan, 2000). Shortly after the mine commenced its STD system, local fishermen began to report fish kills and tailings dispersal onto nearby fringing coral reefs. The STD system also suffered a pipe burst in 1998, which released more tailings into waters close to the beach community of Buyat Pantai (Figure 2). The mine was closed at the height of the controversy over the impacts of its STD system, not because of the controversy, but because the ore deposit had been fully exploited. Shortly after the mine closed, three executives from the mining company were arrested and tried on environmental charges related to contamination of the bay. The mining company executives were acquitted, but the company later reached an out-of-court settlement in a civil suit. Most of the villagers of Buyat Pantai were eventually resettled to a different location after the mine closed in 2004, although lack of infrastructure in their new location made the transition difficult (Siregar, 2005).

Environmental consultants hired by the mining company carried out an environmental impact assessment (AMDAL) before the mine opened (PTNMR, 1994), and then a separate environmental risk assessment after the mine opened and local villagers began to complain of

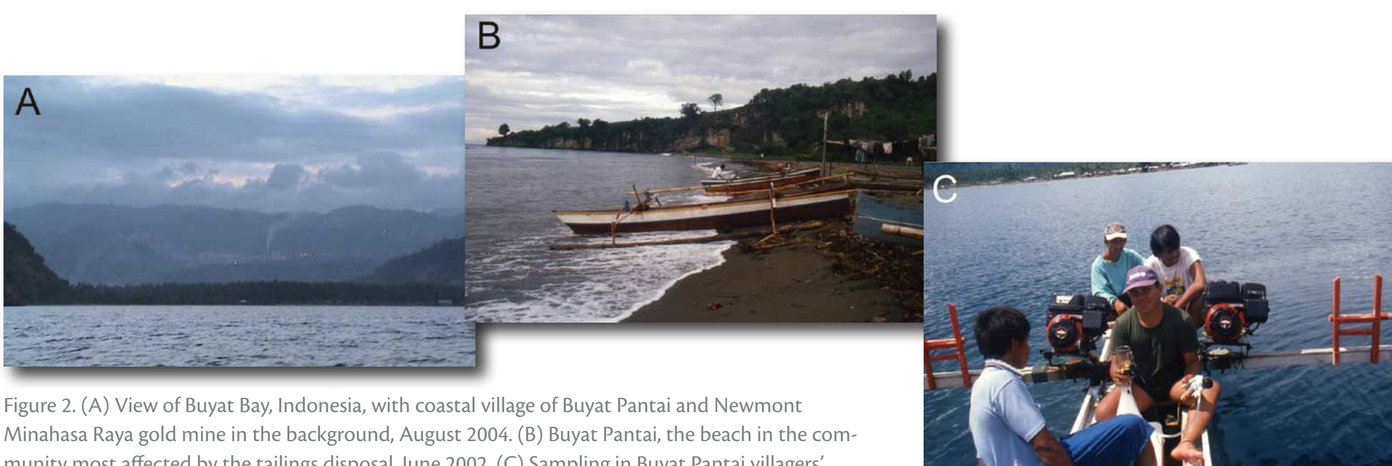

Figure 2. (A) View of Buyat Bay, Indonesia, with coastal village of Buyat Pantai and Newmont Minahasa Raya gold mine in the background, August 2004. (B) Buyat Pantai, the beach in the community most affected by the tailings disposal, June 2002. (C) Sampling in Buyat Pantai villagers' motorized canoes, June 2002.

fisheries and health impacts (Shepherd-Miller Inc., 2001). Importantly, the AMDAL included the determination of sediment trace element concentrations from a number of locations surrounding the mine, facilitating before-and-after studies. Although a before-after-control-impact (BACI) study was not possible for this mine, sediment trace element concentrations could be compared for similar locations before and after the STD operations. The environmental risk assessment studied contaminant concentrations in a variety of fish species caught in Buyat Bay (the site of the STD system), an adjacent bay, and open waters offshore (Shepherd-Miller Inc., 2001).

Tailings Dispersal

Sediment samples collected six and eight years after the beginning of STD operations showed that tailings had dispersed from the intended deposit site at 82 m depth upward into shallower water throughout Buyat Bay, the small bay in which the tailings were disposed (Figure 3). The tailings pile height itself was about 11 m above the seafloor in December 2000 (PTNMR, 2002a). A seafloor survey determined that the tailings pile occupied an area of 300 × 600 m in December 1999 (0.18 km^2) and 380 × 750 m in December 2000 (0.285 km^2; PTNMR 2002a) inside a small submarine valley at the mouth of Buyat Bay, and above a 100 m deep shelf that extended seaward for approximately 5 km. Mining company surveys identified tailings dispersal up to the 50 m depth contour, with tailings thicknesses ranging from 20–40 cm away from the main tailings pile. The mining company attributed these dispersed tailings to a brief period of widespread tailings discharge when the mine first commenced STD operations in March 1996, before the mouth of the outfall pipe became covered in tailings (PTNMR, 2002a).

Tailings were identified visually by their pink to rusty brown color (Figure 4), and chemically by the relative abundance of different trace elements in the tailings, especially the very high ratio of As and Sb to lighter metals such as Cr, Cu, Co, and Ni, which were found in approximately equal concentrations in fluvially derived, reference, and pre-mine sediments (Figure 5; Edinger et al., 2007). Tailings were found in fringing coral reef sediments in waters as shallow as 20 m (Edinger et al., 2007), and corals smothered in red fine-grained sediment resembling the tailings were observed in waters as shallow as 10 m (Figure 6; see video and figure at http://www.tos.org/oceanography/archive/25-2_edinger.html#supplement).

When whole sediments were sieved to the < 63 µm fraction, arsenic

Figure 4. Photo of tailings as recovered by grab sampler, June 2002.

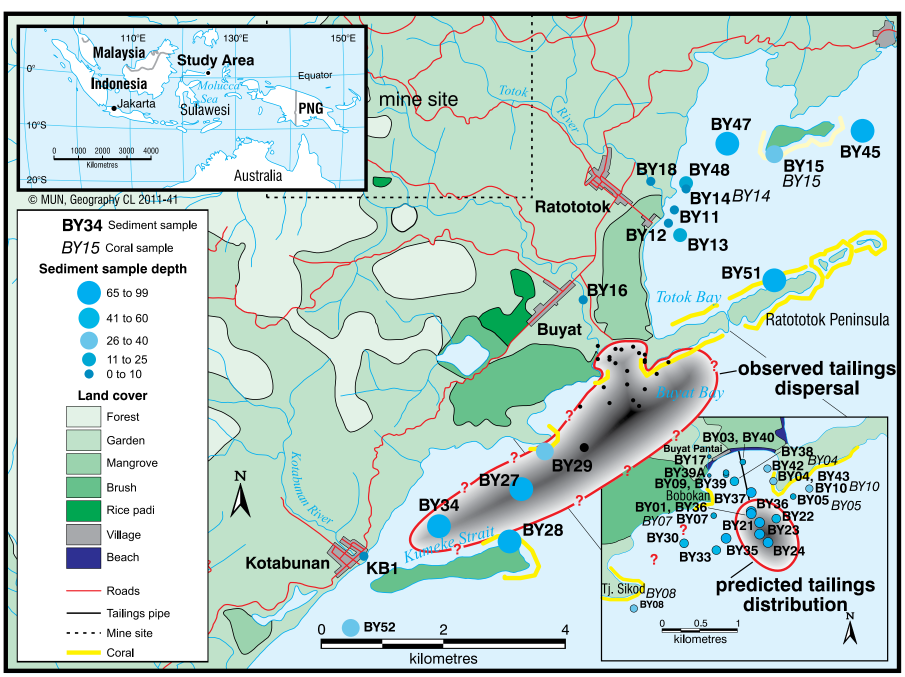

Figure 3. Detail map of sediment samples and coral reefs near Newmont Minahasa Raya gold mine, Indonesia. Inset map indicates tailings pipe and modeled distribution of tailings (PTNMR, 2002b), while the broader map shows observed dispersal of tailings. Question marks along the edge of the observed tailings dispersal area indicate a lack of observations seaward, eastward, and where sampling did not detect the edge of the tailings contaminated area. *Modified from Edinger et al. (2008)*

concentrations in reef sediments at the fringing coral reef closest to the tailings outfall were > 250 ppm, 15–20 times higher than the pre-mining and uncontaminated reference samples, indicating that the tailings comprised up to 30% of the mud fraction of sediment at this site (Edinger et al., 2008). Antimony concentrations were consistently high in all the tailings-contaminated sediments, but relatively insoluble antimony oxides dominated antimony mineralogy in the tailings (Blackwood and Edinger, 2007). Despite the mining company assertion that tailings distributed throughout the bay in 1996 were subsequently buried by fluvial sediment, grab samples taken in 2002 and 2004 with a hand-held grab sampler with 15 cm scoops recovered surficial sediments bearing arsenic and antimony concentrations, suggesting that 30–60% of the fine-grained fraction was composed of tailings (Figure 5). These high concentrations can be explained either by continued dispersal of tailings from the tailings pile to the shallower portions of the bay, or by bioturbative mixing of combined tailings and post-tailings sediment. Although diagenesis could contribute to arsenic enrichment of surface sediments (e.g., Martin and Pedersen, 2002), such enrichment would seem unlikely for antimony, which was mostly present as highly insoluble antimony oxide. The relatively constant proportions of arsenic and antimony in the tailings-contaminated sediment allowed tracing of tailings dispersal, and strengthens estimates of the proportion of fine sediments composed of dispersed tailings based on the elevated concentrations of these elements.

Coral skeletons can record the history of metals pollution from mine tailings and other sources (David, 2003; Reichelt-Brushett and McOrist, 2003). Live *Porites* coral skeletons from the reef closest to the tailings outfall contained higher concentrations of chromium, copper, cobalt, lead, arsenic, antimony, and thallium than corals from a reference reef.

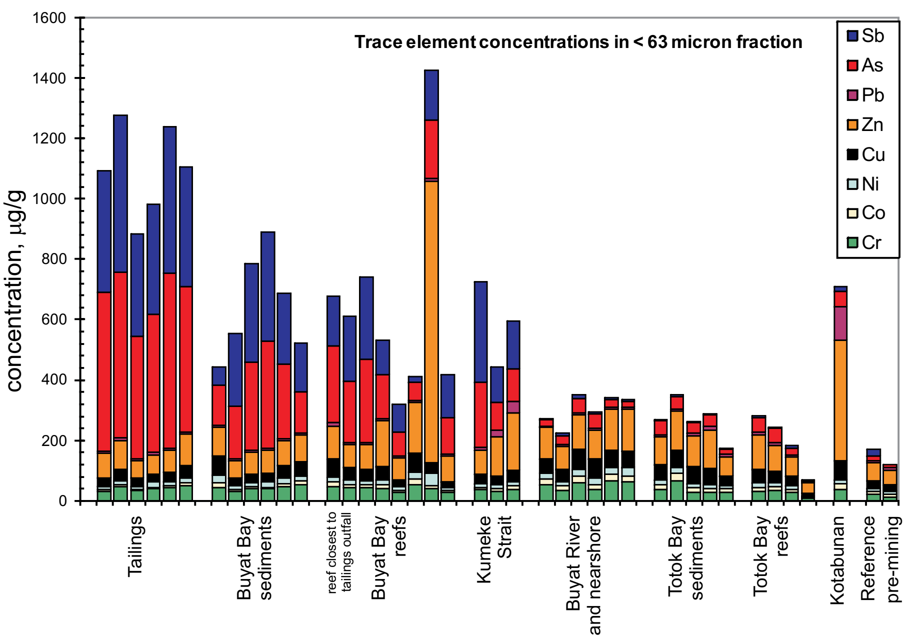

Figure 5. Trace element concentrations in sediment samples surrounding Newmont Minahasa Raya gold mine, Indonesia. STD affects Buyat Bay, while artisanal gold mining using mercury amalgamation affects Totok Bay and Kotabunan watersheds. *Modified from Edinger et al. (2008)*

Figure 6. Photos of reefs in Buyat Bay area, June 2002. (A) Site BY04 (see Figure 2 for site locations), a reef closest to tailings outfall at 3 m depth. Note mixture of living and dead corals, and the high water turbidity, which is indicated by high scatter (vs. photo C). (B) Site BY04 is a reef closest to tailings outfall at 5 m depth. Note abundance of sediment on the seafloor, some of which is smothering corals. The sediment visually and chemically resembles tailings. (C) Site BY06 is a reef approximately 2 km seaward of tailings outfall, with no evidence of contamination. Note excellent water clarity, high live coral cover, and diversity.

Ironically, the differences among reefs were statistically significant for most of the trace elements, but not for arsenic. Tailings-derived trace elements, particularly arsenic and antimony, were contained in the coral skeletons as microscopic particles of sediment, rather than as dissolved metals incorporated directly into the coral skeleton (Edinger et al., 2008). Arsenic is one of several mining-derived toxic trace elements in which the size of the atom is incompatible with the aragonite crystal lattice that makes up the coral skeleton (Howard and Brown, 1984). The high within-sample variability in arsenic concentrations associated with the uneven distribution of sediment particles within the skeletons blurred the broader pattern, and explained the lack of statistical significance in differences in coral skeleton arsenic concentrations among reefs. Although dead corals were abundant on the reef closest to the tailings outfall, and many of the dead or dying corals appeared smothered by sediments the color of the tailings, we have no direct chemical evidence of the tailings' toxicity to the corals. Rather, the coral skeletons appeared to be passive recorders of the sediment contamination. Fishermen reported reef fish with tumors that were caught near both the reef closest to the tailings outfall and other reefs subjected to tailings dispersal.

The spatial distribution of tailings-contaminated sediment extended as far as 3.5 km from the end of pipe and over an area of at least 4.5 km^2, and probably more. It is not possible to determine accurately the proportion of the total tailings volume that dispersed into shallow water because the total area affected by tailings dispersal is not known. A maximum dispersal distance can be determined shoreward and to the southwest, but seaward dispersal, and eastward dispersal along the Ratototok Peninsula (past station BY10; see Figure 3 for location) were not sampled. Very crude estimates of total tailings dispersal were calculated based on the following assumptions, with contamination zones estimated from the degree to which arsenic and antimony concentrations were elevated above background, in conjunction with mining company estimates of tailings thickness away from the tailings pile (PTNMR, 2002a). Areas were estimated as the minimum-size polygon containing the sampling points within zones of high, medium, and low tailings contamination, measured in ArcMap 9.3. First, the volume of tailings in the tailings pile itself was measured as the volume of a cone of 0.285 km^2 basal area and 11 m in height (PTNMR, 2002a). The volume of tailings dispersed to inner Buyat Bay was estimated as a 30 cm thick wedge of tailings in the 0.5 km^2 highly contaminated zone of inner Buyat Bay, with the thickness estimate based on mining company core-based estimates of 20–40 cm thickness (PTNMR, 2002a). In the ~ 2 km^2 documented moderately contaminated dispersal zone immediately outside Buyat Bay, including reef samples BY05 and B10 (see Figure 3 for location), tailings depth was estimated to be one-third that of the inner bay, hence, a depth of 10 cm, less than the mining company estimate of 15 cm tailings thickness to the south and west of the tailings pile (PTNMR, 2002a). Finally, for the remaining 2.5 km^2 of the tailings dispersal area as far southwest as Kumeke Island, tailings depth was assumed to be < 10% of that in the inner bay, or 2.5 cm. These calculations suggest that approximately 70% of the tailings remained in the area of the modeled distribution, while about 30% of the tailings dispersed away from this zone. Confidence in these estimates of total dispersal is low, and the total volume of tailings dispersed away from the main pile is probably underestimated. Based on mining company discharge rates of 123.6 m^3 hr^{-1} at 50% water content, the volume change of the tailings pile between 1999 and 2000 was approximately 62% of the annual tailings solid volume discharge, without accounting for compaction. The difference in volume can probably be attributed to a combination of ongoing tailings dispersal and compaction of the tailings pile after initial dewatering. From the standpoint of the villagers, dispersal into the bay, and onto their fishing grounds within the bay and along the fringing coral reefs, was the most serious impact.

Despite the crude nature of these estimates of total dispersal, the dispersal data are sufficient to demonstrate that the observed dispersal area was more than 10 times greater than the predicted dispersal area based on the tailings modeling and mine closure studies (PTNMR, 2002a,b). Furthermore, according to the environmental impact assessment, the observed tailings dispersal should not have occurred at all. The causal link between tailings dispersal and the observed fish kills and fish tumors in areas of tailings dispersal reported by local fishermen has not been published in the scientific literature. Nonetheless, use of local ecological knowledge (LEK) in fisheries management, where compared with scientific survey data, has repeatedly demonstrated the validity of LEK (e.g., Gass and Willison, 2005).

The mining company based its tailings distribution models on the assumption of a seasonally stable thermocline at 50 m depth, slightly above the depth of the tailings pile (PTNMR, 1994, 2002b), yet the CTD (conductivity-temperature-depth) profile data included in the mine's environmental impact study (PTNMR, 1994) indicate high seasonal variability in thermocline depth and intensity, with thermocline depth ranging between 50 and 100 m. A subsequent study based on CTD data collected in 1997, shortly after the mine opened and fishermen began reporting tailings dispersal, also showed high seasonal variability in thermocline depth and stability, with the thermocline as deep as 80 m, and density stratification collapsing in July and August (Figure 7; Prisetiahadi and Yanaga, 2008). The oceanographic study recommended a minimum depth of the tailings pile at 135 m, based on the seasonal variability in stratification. To reach this depth, the tailings pipeline would have had to be at least 5 km long. Furthermore, the environmental risk assessment for the mine identified possible internal waves propagating along the thermocline (Shepherd-Miller Inc., 2001). One possible explanation for how the tailings were dispersed is that internal waves propagating along the seasonally variable thermocline entrained the tailings, allowing dispersal by the internal waves, or by tidally induced currents. The fact that all the necessary oceanographic data to indicate seasonal variation in the thermocline depth had been collected before the STD operations commenced is important, because it shows that the mining company could have identified the risk of tailings dispersal based on the data available before they began dumping the tailings.

Ironically, company monitoring reports, the company's mine closure study (PTNMR, 2002b) and a Commonwealth Scientific and Industrial Research Organisation (CSIRO) consulting report commissioned by the mining company (Apte et al., 2004) found a lack of impact on fringing reefs and associated sediments. Although the mining company's water and sediment quality monitoring sampled the immediate environment of the tailings outfall, the reef monitoring studies were all carried out on the fringing reefs outside the bay, and did not include the reef closest to the tailings outfall (e.g., Lalamentik, 2000). To achieve methodological consistency and quality control, the CSIRO consulting report did not use the pre-mining data from AMDAL, and only compared the tailings to several sites that were considered to be outside the zone of tailings distribution. By calculating average background values based on multiple sites, some of which were incorrectly assumed to be unaffected, the CSIRO consulting report ascribed higher concentrations and higher variability to background conditions than were suggested by the pre-mining data (Edinger et al., 2007, 2008). In fact, several of the sites presumed to be unaffected for the CSIRO report were shown to have a tailings-derived sediment influence (Edinger et al., 2007).

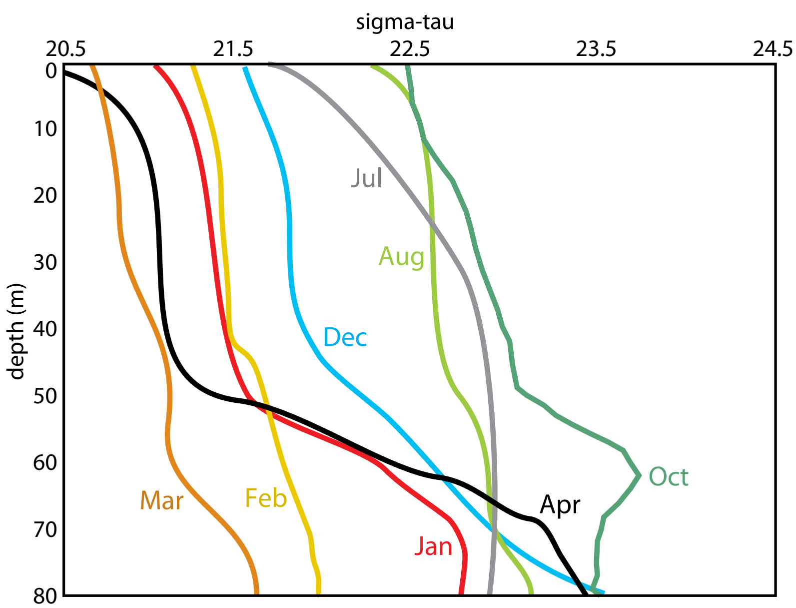

Figure 7. Seasonal variation in water density (sigma-tau) profiles based on conductivity-temperature-depth (CTD) data near Buyat Bay submarine tailings disposal (STD) outfall. *Redrawn and simplified from Prisetiahadi and Yanaga (2008)*

Ore Processing and Tailings Geochemical Stability

The deposit exploited at the NMR mine was a Carlin-like hypothermal sediment-hosted gold deposit (Turner et al., 1994). Typical of Carlin-type deposits, the NMR mine had mostly refractory disseminated sulfide gold ore with As-Sb-Hg-Tl anomalies, in which gold was hosted as microscopic inclusions within arsenian pyrite, itself precipitated into a silica-rich limestone. The environmental impact assessment for the mine identified arsenic and mercury as the major contaminants of concern, and tailings treatment was designed to reduce the solubility of these elements. Although antimony has since been recognized as a widespread contaminant of concern (Reimann et al., 2010; Wu et al., 2011), it was not considered important by the mining company at the time of the environmental impact assessment. Extraction of the gold required oxidative treatment based on roasting, followed by cyanidation and electro-winning. Whole ore was roasted at 550–580°C in the presence of limestone and dolomite from the host rock, in the hope of capturing some arsenic as magnesium arsenate. Tailings were treated with ferrous sulfate to produce two other arsenic-bearing phases, ferric arsenate and arsenical ferrihydrite (Weeks and Wan, 2000). These aspects of tailings treatment were intended to stabilize arsenic in the tailings, in order to minimize the risks of arsenic toxicity after tailings were deposited into nearby Buyat Bay.

The mine collected water samples a few meters above the tailings pile as part of its environmental monitoring program, and consistently reported low dissolved arsenic concentrations in the water above the tailings pile. Due to ongoing environmental concerns about the STD system, the mining company also installed sediment pore water samplers in four locations around the bay (PTNMR, 2002b). Near the base of the reef closest to the tailings outfall, the sediment pore water samplers found maximum concentrations of dissolved arsenic of 2,000 μg L^{-1} about 20 cm below the sediment-water interface, and declining toward the sediment surface. This pattern of dissolved arsenic dissolution within sediment pore water matches predictions based on increased solubility of metastable arsenic phases under reducing conditions (Rochette et al., 1998; Zhang and Moore, 1997; Zhang et al., 2005). Ironically, dissolved arsenic concentrations at 20 cm sediment depth were higher in the tailings-contaminated sediments at the base of the reef than in the tailings themselves, where maximum pore water concentrations were 300 μg L^{-1}. This difference likely resulted from higher organic content in the tailings-contaminated sediment than in the tailings themselves, causing more strongly negative redox conditions, which promoted greater arsenic dissolution (Martin and Pedersen, 2002; Blackwood and Edinger, 2007) and methylation of arsenic that in turn increased its bioavailability. Alternatively, the difference in dissolved arsenic concentrations in the sediment pore water could be ascribed to the high sediment accumulation rate at the tailings outfall, such that the dissolved arsenic concentrations in sediment pore water at the tailings outfall increased continuously with depth in the sediment profile.

The distributions and concentrations of dissolved arsenic in sediment pore water matched the results of a sequential extraction study that found up to 30% of the arsenic within the tailings to be in weak-acid soluble phases, and a further 20% in metastable phases such as ferric arsenate and iron and manganese oxy-hydroxides (Blackwood and Edinger, 2007). For example, ferric arsenate and calcium arsenate, two of the tailings components that probably dissolved in the weak acid extraction, are relatively insoluble under aerobic conditions, but dissolve readily under reducing conditions (Rochette et al., 1998; Zhu et al., 2005). The concentration of labile (weak-acid soluble) arsenic in the tailings was more than four times greater than the probable effect level for total arsenic in marine sediments (41.6 mg kg^{-1}; CCME, 2002), implying significant potential for arsenic toxicity in the mine tailings, both at the end of pipe and in reef and bay sediments into which the tailings were mixed as they dispersed. The sequential extraction study, combined with the sediment pore water profiles and the dispersal of the tailings onto reefs close to the tailings pipe, suggests that the STD system in Buyat Bay polluted the bay with geochemically unstable forms of arsenic (Blackwood and Edinger, 2007).

Mercury Contamination at Newmont Minahasa Raya

Mercury was one of the most contentious topics in the NMR example because of the widespread mercury contamination from artisanal gold mining of native gold deposits in volcanic rocks surrounding the refractory Carlin-like deposit. Concentrations of total mercury in marine sediments declined exponentially with distance from the mouth of the Totok River, in whose watershed artisanal mining is practiced (Edinger et al., 2007). Concentrations of total mercury and methyl mercury in estuarine and marine sediments were highest in Totok Bay (affected by artisanal gold mining), intermediate in Buyat Bay (the STD site), and lowest in Bajo, a reference site with a river draining a mapped but unexploited gold deposit in volcanic rocks (Lasut et al., 2010). The ratio of methyl mercury to total mercury was the same in all three locations, indicating that mercury from mine tailings, artisanal mining, and natural, undisturbed geologic sources all underwent methylation in equal proportions. In all three locations, methyl mercury accumulated in seaweed, invertebrates, and fishes, and methyl mercury concentrations in biota increased with trophic level. Analysis of human hair samples showed that adult men, but not women, in Buyat Pantai, the village closest to the STD outfall, had elevated body burdens of methyl mercury, compared to the reference village. The most probable pathway of contamination was through consumption of fish caught in Buyat Bay, where STD-derived mercury was incorporated into the marine food web, including several food-fish species (Lasut et al., 2010). The differences between men and women probably derive from greater fish consumption by men than by women. Although this study documented mercury contamination of the food web from gold mine STD, it also highlighted the biological impact of mercury from artisanal gold mining, which affects a much greater number of watersheds in North Sulawesi than does industrial gold mining.

> "HAD THE MINE MADE A LONG PIPE TO REACH DEEPER WATER, THE DISPERSAL ONTO LOCAL FRINGING REEFS MIGHT HAVE BEEN AVOIDED, BUT THE INHERENT MINERALOGICAL AND GEOCHEMICAL INSTABILITY OF THE TAILINGS WOULD HAVE REMAINED A PROBLEM, JUST IN A DIFFERENT PLACE."

An additional source of mercury contamination from the NMR mine was the ore roasting, in which mercury was volatilized. Although the mine installed mercury scrubbers on the smokestacks from its roaster, they were not functional for most of the mine's lifespan, causing the mine to release 17–30 tonnes of mercury over the eight years of mine operations. The mining company admitted to extensive airborne mercury emissions during the height of the STD controversy in 2004. The fate of the airborne arsenic, antimony, and mercury emissions from this mine has not been studied.

SUMMARY | A BAD APPLICATION OF STD, OR A BAD TAILINGS MANAGEMENT TECHNIQUE?

Given the intense oxidative processing required for refractory gold ores, and the potential reactivity of the resulting arsenic forms in tailings, STD is probably inappropriate for Carlin-type gold deposits (Blackwood and Edinger, 2007). These deposit types also contain mercury, which could undergo similar types of transformations, rendering the mercury biologically available, as observed with mercury methylation and incorporation into the food chain in Buyat Bay (Lasut et al., 2010). Furthermore, the shallow depth of the tailings outfall and seasonal thermocline variability in the NMR mine example resulted in dispersal of the tailings into shallow water and fringing reefs that were regularly used as fishing grounds by the local population. Dispersal of the geochemically unstable ore into shallow waters exploited as fishing grounds provided a potential pathway for arsenic and mercury contamination of the marine food web, including fish species consumed by local villagers. Had the mine wanted to extend the pipe to reach a depth > 100 m and slope > 12°, as recommended by STD proponents, the pipeline would have had to be > 5 km long, with the attendant increased risk of pipe bursts. Had the mine made a long pipe to reach deeper water, the dispersal onto local fringing reefs might have been avoided, but the inherent mineralogical and geochemical instability of the tailings would have remained a problem, just in a different place. Furthermore, there have been no studies of the deepwater (> 200 m) invertebrate or fish faunas of the Buyat-Ratototok region, but diverse deepwater coral and fish faunas near North Sulawesi, including an Indonesian coelacanth species, indicate a potential for high biodiversity (Fricke et al., 2000). Thus, the NMR case study represents a poorly executed application of a tailings management technique that was also inappropriate for its ore type. The mining company argued for STD on the basis of the region's high rainfall and seismic activity, but did not perform a rigorous evaluation of terrestrial vs. marine tailings disposal options (PTNMR, 1994;

Shepherd-Miller Inc., 2001).

In the other gold mines where STD has been applied or considered, the reported impacts are highly variable. The Lihir and Misima gold mines have both described some impacts on the surrounding environment from STD, including sedimentation (Rotmann and Thomas, in press) and metals uptake by corals (Fallon et al., 2002), and mercury and arsenic incorporation into fishes (Fry et al., 2006; Brewer et al., 2007; Shimmield et al., 2010). Relatively little has been published on the impacts of STD at the Batu Hijau porphyry copper-gold deposit, whose tailings contain less than 3 ppm arsenic. An experimental study on meiofauna recolonization of the Batu Hijau tailings found normal shallow-water meiofauna within less than one year of deployment (Gwyther et al., 2009), although the interpretations of this study are not readily applicable to other mines, or to larger invertebrates. Copper sulfides in subaerially exposed stockpiled low-medium grade Batu Hijau ore were more unstable than those in unoxidized higher-grade tailings (Sahami et al., 2011).

Pre-mine experimental field or lab studies of possible STD for gold mines in Alaska and Greenland have found measurable impacts of variable and perhaps uncertain duration (Johnson et al., 1998a,b; Kline and Stekoll, 2001; Matthies et al., 2011). In the Kensington gold mine in Alaska, a carbonate-hosted vein gold deposit with low arsenic content tailings, STD and dry-stack tailings management options were rejected in favor of subaqueous tailings disposal in a natural lake, the level of which was raised by a dam (USFS, 2011). This subaqueous tailings disposal was only permitted after a controversial US Supreme Court decision that the tailings could be considered "fill" rather than toxic sediment. Preliminary testing of tailings from the nearby historical Alaska-Juneau gold mine, which was considered for re-opening in the 1990s, found that juvenile flatfish avoided the tailings (Johnson et al., 1998a), and that the tailings had the potential to impact spawning success and behavior of tanner crabs, a commercial fishery species (Johnson et al., 1998b). Preliminary analysis of geochemical stability of gold mine tailings from the Nalunaq mesothermal gold-vein native gold deposit in Greenland, in which native gold was associated with arsenopyrite in igneous rocks, also suggested arsenic mobility. A 20-week experimental lab study prior to potential STD indicated instability of cadmium and arsenic in the tailings under seawater (Matthies et al., 2011). The authors of that study recommended longer-term field testing to ensure stability of arsenic and cadmium before further consideration of plans for STD in this high-Arctic gold mine. The instability of arsenopyrite under the reducing conditions of a lab study (Matthies et al., 2011) and the inherent toxicity of arsenic and mercury, combined with the potential for tailings dispersal in unanticipated directions, suggest that STD is probably inappropriate for all arsenic-rich gold ores.

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